32nd Congress of the International Council of the Aeronautical Sciences
September 6-10, 2021
Pudong Shangri-La, Shanghai, China

DEVELOPMENT OF ADVANCED DESIGNS OF GAS TURBINE ENGINES FROM POWDER COMPOSITIONS

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Abstract

The usage of advanced powder technologies (additive methods and hot isostatic pressing) to create parts and assemblies of promising gas turbine engines, in particular turbine wheels, gradient blisks, and blades, is discussed.

Keywords: powder technologies, gas turbine engines, wells, blades

1. Introduction

In various technology fields, the need for parts and assemblies with improved performance characteristics, such as strength, wear resistance, and the ability to work in aggressive environments, is constantly increasing. The shape and dimensions of the blanks for such products should be as close as possible to the geometry parameters of the parts.

Traditional technologies based on stamping, forging, precision casting, or forming face serious limitations in the production of such blanks due to significant difficulties meeting the requirements for geometric complexity, the given level of accuracy, and the distribution of service and technical characteristics of the material. Recently, progressive technological processes have been developed globally to produce structural materials by spraying liquid alloys at a high speed as granules or other small particles and solidifying them. Subsequently, blanks close in shape and size to the finished part are produced from them. Such powder technologies include hot isostatic pressing (HIP) and various methods of additive technologies (AT).

Currently, 3D printing is widely used in areas such as automobile, airplane, and engine production. This became possible because 3D printing fully meets the industry requirements in the production of complex metal parts.

Gas turbine engine (GTE) parts are objects for which it is rational to use these technologies for manufacturing. HIP has long been widely used for serial production of parts such as turbine disks from granulated disk alloys [1]. The most interesting application of this technology is in the production of one-piece impellers (blisks), consisting of disks made of a granulated alloy and cast blades [2, 3]; functional-gradient disks, consisting of granules of different sizes or different alloys [4-7]; and other similar items.

Various GTE parts are already manufacturing with the help of AT [8. 9]. For example, Avio Aero uses serial production of TND turbine blades made of titanium aluminide by electron beam sintering for the GE9X engine [10]. The titanium case of the Leap1B engine center support is also produced. Parts of the combustion chambers (the fuel nozzle for engines CFM International's LEAP-1A, 1B, and 1C, Siemens' SGT-750 gas turbine burner swirler, and many others) are already prepared for serial production.

One of the main GTE parts that determine their characteristics is turbine wheels, which operate under high non-stationary external loads and temperatures during aircraft maneuvering. Some large parts, such as compressor wheels and turbines in GTEs, have a large mass and are particularly important engine components because their failure leads to the non-localized destruction of the entire engine. Therefore, one of the main tasks in the development of GTE parts is to reduce the weight while satisfying the mandatory strength reliability requirements. This paper discusses the use of powder technologies to create GTE turbine wheels.

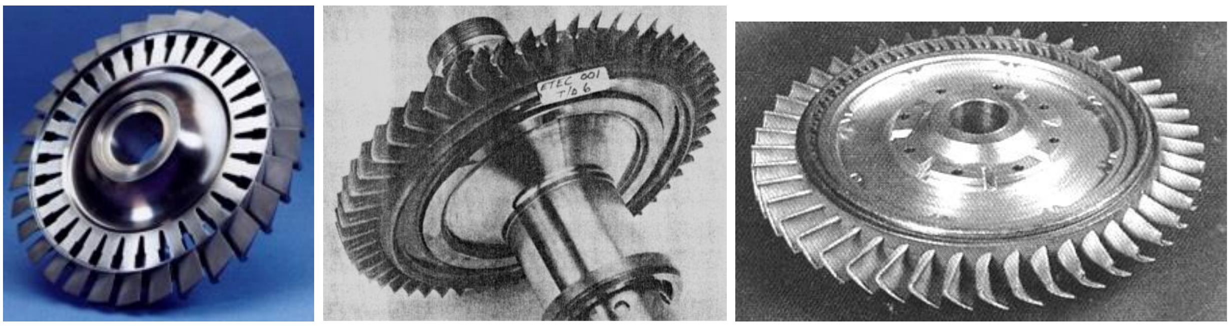
2. Constructive and technological solutions for creating turbine wheels

Impellers are traditionally assembled from separately cast blades and disks manufactured by mechanical granular metallurgy methods. Different high-temperature nickel alloys are used for these parts due to their different operating conditions. High-temperature turbine disks operate under high centrifugal loads and relatively low temperatures, varying from hub to rim from 400 to 700°C. However, the blades are exposed to centrifugal forces and high gas temperatures up to 1000–1100°C. This dictates the need to cool the blades with air that enters the internal channels. Thus, the blade is a complex hollow structure containing various internal elements, such as baffles, pins, and gratings. One feature of the blade-to-disk connection is the presence of stress concentrators. In turbine wheels, the lock connections between the blades and disk are stress concentrators. The values of the stress concentration coefficient in these elements can reach 2.5–4.5. This leads to high voltages in the lock connection and, as a result, to resource limitations. The design of the disk rim takes into account the placement of the required number of blades in the wheel and ensures the strength reliability of the lock connection, which affects the dimensions of the rim and the mass of the wheel.

One-piece structures are made with uncooled blades and are not suitable due to previously described differences in the operating conditions of the blades and disk and, accordingly, the requirements for their materials. In addition, the presence of casting pores in such wheels does not allow them to be used as critical parts.

The solution to the problem may be the use of turbine impellers in the form of bimetallic blisks. In the design of a turbine impeller without blade-to-disk joints, there are no stress concentrations in this zone. Therefore, the blisk rim can be much smaller. This reduces the centrifugal load on the wheel hub and, therefore, the mass of the entire wheel. The static strength and cyclic durability can be increased [11, 12].

Fig. 1 shows examples of monowheels made of dissimilar materials with cooled and uncooled blades. Honeywell Hamilton & Sundstrand manufactured a bimetallic monowheel with uncooled blades for the second stage of the APU turbine for Boeing and Airbus aircraft. A blisk with uncooled separately cast blades made of MarM-246 alloy is connected to the disk made of NF3 by the HIP method (Fig. 1a). The blisks have successfully completed flight tests on 10 Boeing aircraft and 10 Airbus aircraft. The same technology is used for the wheel of the BMW-RR T118 engine and the AGT250/T63-A700B helicopter engine. Pratt and Whitney Co. investigated the simultaneous attachment of blades to a turbine disk by friction welding. Williams Int. manufactured a small-sized blisk from three different alloys with cooled blades (Fig. 1b) for an unmanned vehicle engine (blades: CMSX4; disk rim: MarM-247; blade and disc hub: AF2-DA). Here, air is supplied to the blades through channels in the disk from the hollow shaft. Allison tested a bimetallic blisk of an HPT turbine with a granulated alloy hub and transpiration-cooled single-crystal blades (Fig. 1c). Blisks with uncooled single-crystal blades are connected to a disk made of a granulated alloy by the HIP method (Figs. 1d, 1e). The bimetallic working monowheel of the HPT (Fig. 1f) was obtained by soldering single-crystal blades of an alloy with a disk made of a modern nickel alloy [13]. The cast blades were connected to the peripheral ring and the disk in a single structure using interlayers of a granulated alloy by the HIP method (Fig. 1g, 1h).



a) b) c)

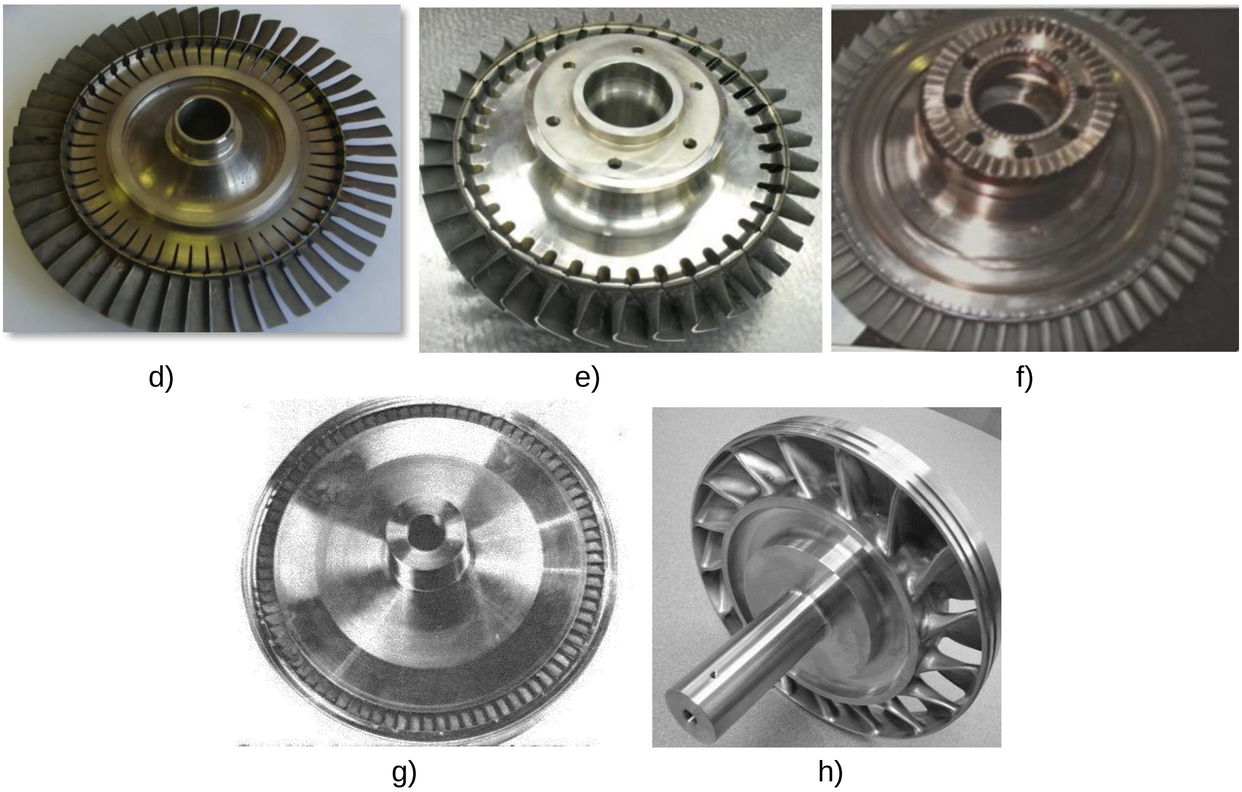


Figure 1 – Examples of monowheels made from different alloys.

Turbine wheel disks, blades, and blisks are examples of the use of powder technologies.

3. Blisk of the turbine

The task of creating a technology to manufacture a bimetallic wheel with cooled blades is urgent [14]. This solution will improve the technical and economic parameters of modern GTEs. An additional benefit can be obtained by using AT to manufacture blades at different stages of their production.

The possibilities of using additive and powder technologies to replace various stages of the traditional method of manufacturing blades based on the design developed for a high-pressure turbine blisk with cooled blades (Fig. 2) are considered here.

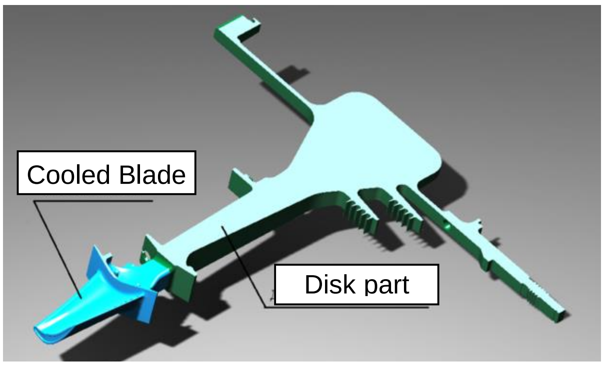


Figure 2 – Model of a monowheel made of different alloys.

3.1 Blades manufacturing

Turbine blades are the most difficult GTE elements to manufacture.

Fig. 3 shows the main steps using traditional precision casting to make blade castings for high-temperature turbines.

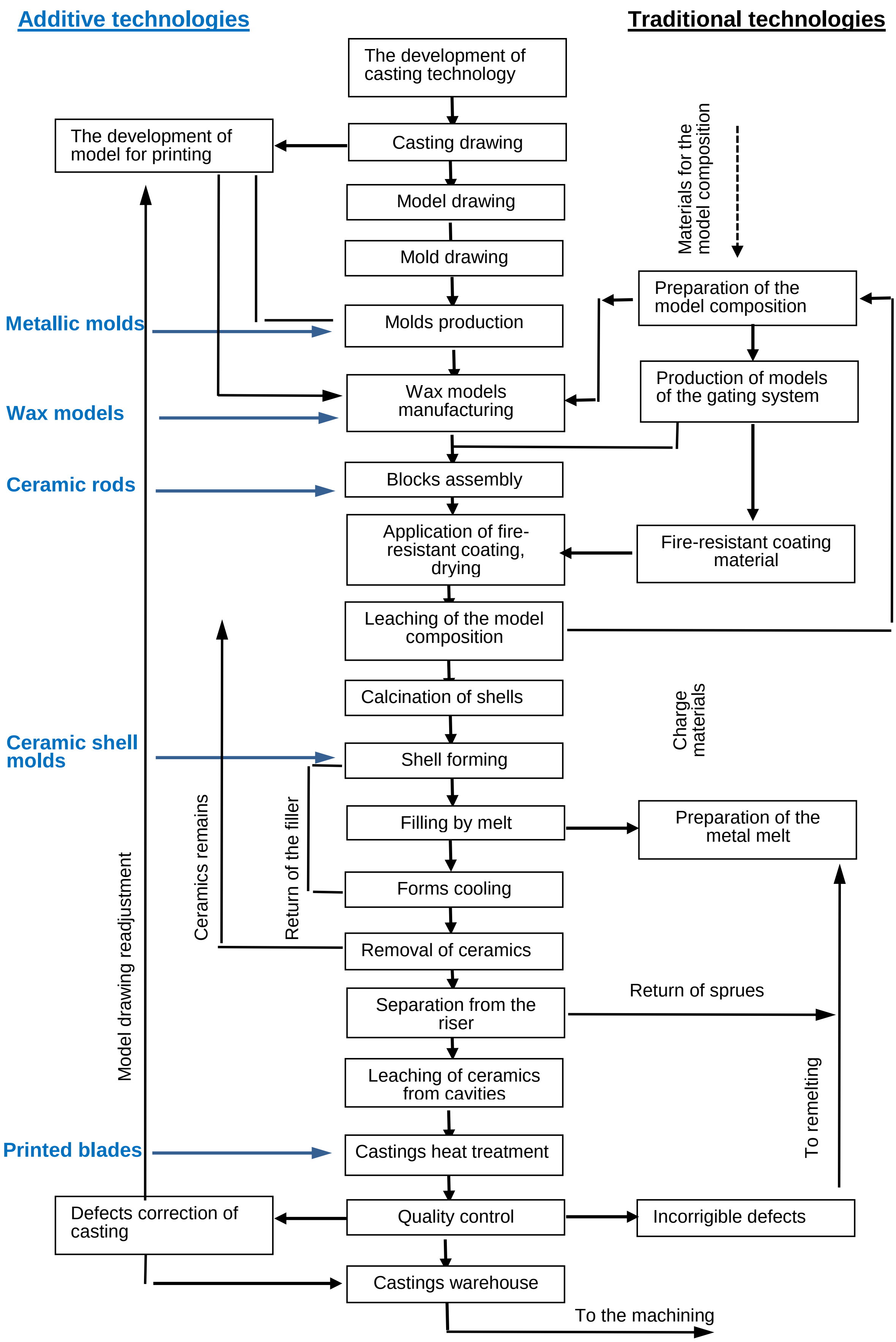


Figure 3 – Technological scheme of the making castings blades.

The traditional investment casting process involves the following steps [15]:

- Design of the casting blank in accordance with the drawing of the part and technical allowances for machining
- Design of the casting model in accordance with the drawing of the casting blank, considering the shrinkage of the model composition and the alloy being melted
- Production of a casting model
- Design and manufacture of molds using mechanical processing
- Pressing of the model composition into the mold
- Retrieval of the model of the future casting after it has cooled and solidified in the mold
- Assembly of several models for the riser to form a gating system
- Formation of a casting mold by covering the model assembly with a suspension and sprinkling it with ceramic powder, followed by drying (repeating the last operation three to four times)
- Removal of castings from the mold of the wax model with a riser
- Drying the shell of the casting mold to remove the remnants of the melted model mass by calcining in electric furnaces
- Hot molding of calcined casings of casting molds and pouring with melt
- Extraction of cooled castings and removal of a ceramic casting mold from their surface
- Separation of castings from the riser
- Leaching of ceramic residues from castings
- Control of geometric parameters and quality of the casting material

To shorten this long chain for the manufacture of casting cooled turbine blades, technological processes can be developed using additive manufacturing methods [8], which will replace part of or the entire manufacturing process [9, 10] (shown in blue in Fig. 2).

- 3D printing of the forming metal elements of the mold to form the outer element for casting a cooled blade
- Production of a burned-out (lost-wax) model of a blade on equipment for 3D printing
- 3D printing of forming metal elements of the mold for slip molding of the inner element (core) of the blade
- 3D printing of a model ceramic rod
- 3D printing of a ceramic shell mold with an embedded core.

Finally, the blades can be made directly by 3D printing without all previous operations.

3.2 Casting models

Based on the 3D casting models developed, various options for its production are discussed: in split steel molds and by AT methods. The technological process of making a casting model by molding in a mold consists of several stages: designing a mold, manufacturing it, placing a pre-made ceramic rod in it, evacuating the mold, pouring a model composition, pressing, extracting and cleaning the burrs, and controlling the model.

The dimensions of the working area of the molds are calculated considering the shrinkage of the model composition and the casting metal during cooling.

3.2.1 Mold making

Manufacturing a mold by machining is a long and complex technological process. In accordance with the mathematical model of the mold, a program for CNC machines is developed. Forgings, rolling, and casting from tool steels are used as blanks for mold parts. The mold plates are first milled. Then they are heat treated. Finishing of the shaping cavities of the matrix and punch is completed by the finishing method—cleaning and scraping some areas in hard-to-reach places (Fig. 4). These surfaces have high precision requirements.

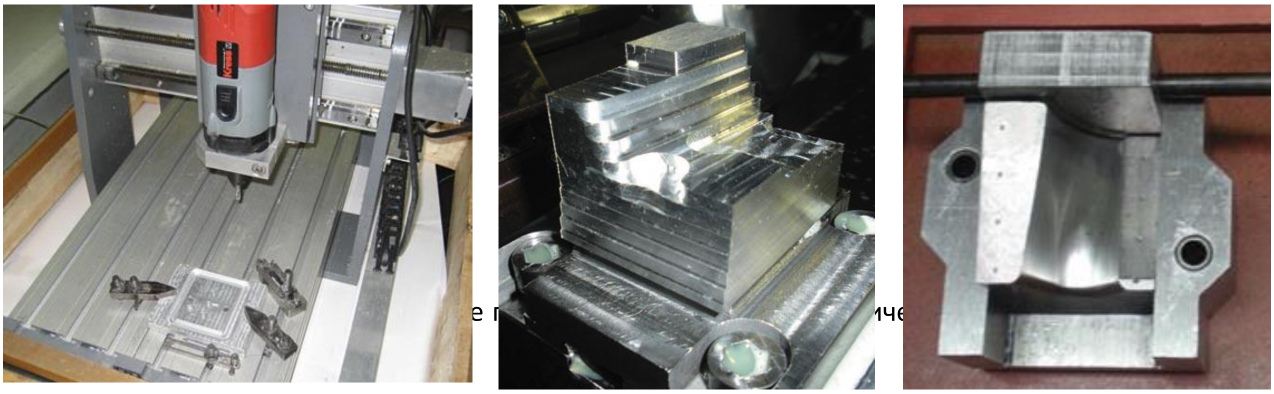
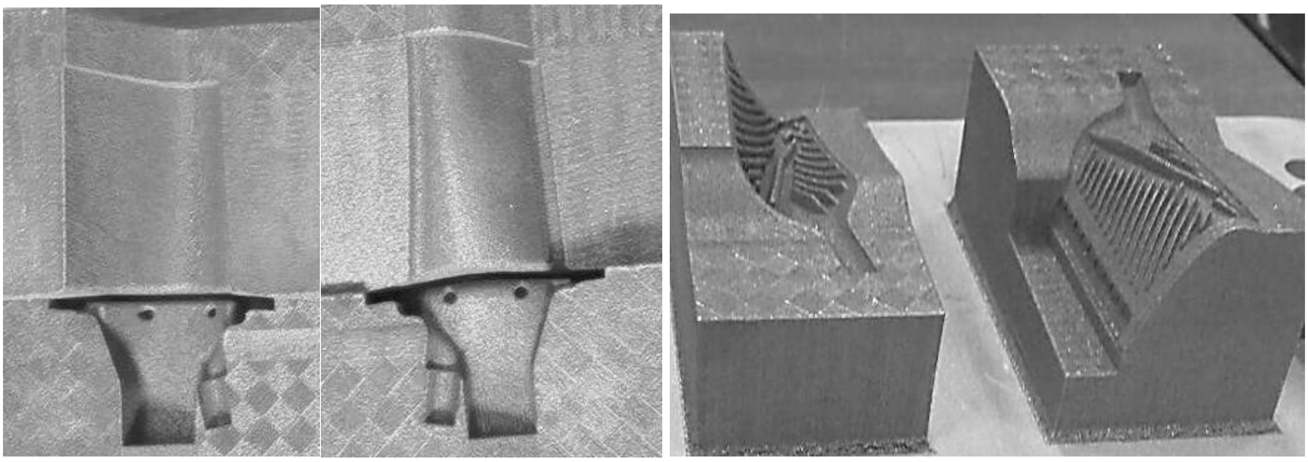


Figure 4 - Making a mold by machining.

By bypassing all the previously described operations, the casting mold (matrix and punch) can be grown on a 3D printer, and the surface of the mold can be cleaned manually. The mold is installed on a thermoplastic automatic machine, and the final product is obtained: burnout (lost-wax) models. Because the mold elements are intended for repeated use in manufacturing, it is advisable to use materials with high hardness. Powder steels with a hardness of 48–55 HRC and wear resistance have been developed for various printer models. Such materials include, for example, CL 50WS LQ and CL 91RW LQ and are used for SLS printing on Concept-Laser installations. Stainless steel powder 17-4PH is also used in ProX 3D Systems printers. A 3D Systems ProX 300 printer was used to manufacture test mold elements. Fig. 5a shows grown mold elements for making burnout models for casting blades. In the same way, a mold can be made for slip molding or the manufacture of a burned-out model of a rod (Fig. 5b).



a) The mold for outer shell b) the mold for rod

Figure 5 - Printed Burnout Molds.

Precision measurements of the printed molds showed good agreement with the models (Fig. 6).

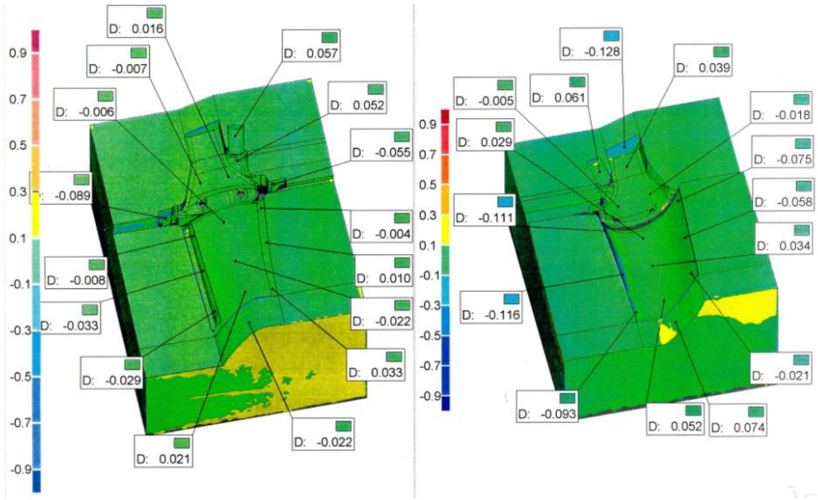


Figure 6 - Results of measuring the accuracy of manufacturing printed molds.

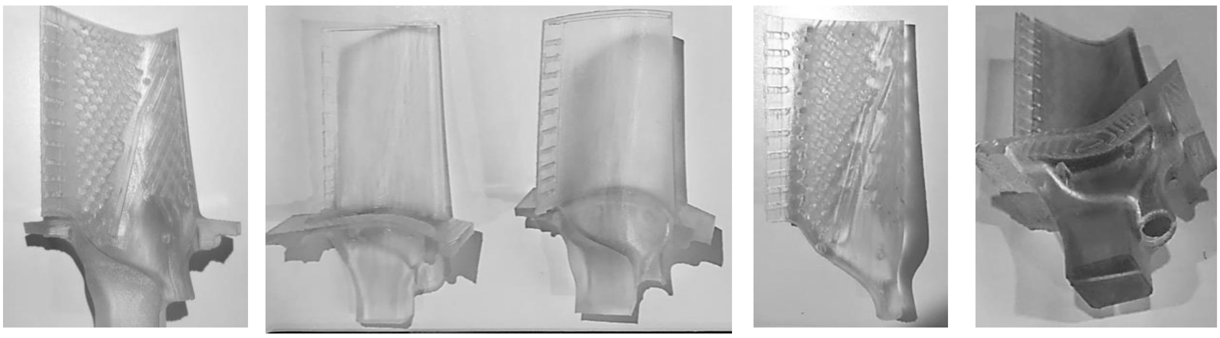
3.2.2 Making a burned-out model of a cooled blade

The stereolithography method was chosen to make a model of a casting. Stereolithography is a technology for manufacturing parts based on a computer three-dimensional model. This process can replace the steps for making metal molds. Stereolithography has a number of significant advantages: the high accuracy of models required for the manufacture of tooling, the possibility of obtaining a high-quality surface, the ability to obtain transparent models for full scale, and other advantages. Testing and full compatibility of the technology of casting metal parts using burned-out patterns with the standard production process.

The best construction accuracy is achieved using stereolithography (SLA) machines. Modern SLA materials have low shrinkage and a definite viscosity, which makes it possible to stably obtain thin layers of up to 0.025 mm during the construction process. The real construction accuracy of SLA machines is 0.025–0.05 mm per inch of linear dimension.

Stereolithographic models of the blade elements were printed on an industrial 3D Systems ProX 800 printer using PolyRay SLA technology.

Fig. 7 shows the models of the blade (7a), outer shells (7b), rod (7c), and assembly unit.



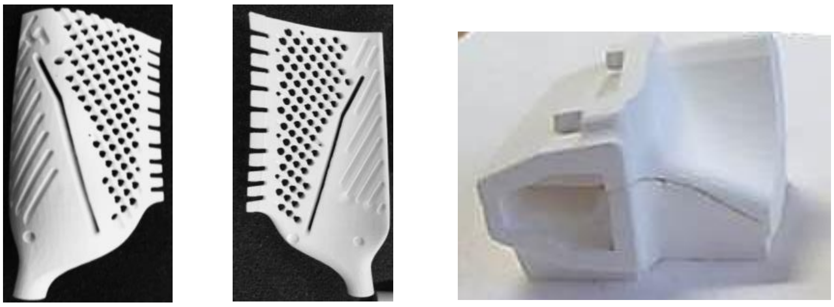
a) blade b) models of outer shells c) rod d) assembly

Figure 7 - Stereolithographic models of blade elements.

3.2.3 Process of making a ceramic rods and shell molds

Instead of making a mold, pressing a model composition into a mold, extracting a model of the core after it has cooled and solidified in the mold, and completing further production operations, a ceramic core can be printed directly from a 3D model. The 3D model of the rod is a complex internal cavity of the cooled blade. The core will serve as a liner in the mold for making the mold and then removing it with an alkali. An industrial 3D printer Ceramaker, manufactured by 3DCERAM, was used to manufacture the rods, with the additive technology of layer-by-layer curing of a ceramic paste. In this case, we used a paste of aluminum oxide Al2O3. This paste has sufficient strength, low warpage, and metal-casting and leaching-out temperature resistance as required by the casting process.

Fig. 8 shows photographs of the printed ceramic tooling for casting blades: the rods (8a) and a trial shell mold with an integrated rod (8b).



a) ceramic rods b) shell with an integrated rod

Figure 8 - Making a ceramic tooling for a blade.

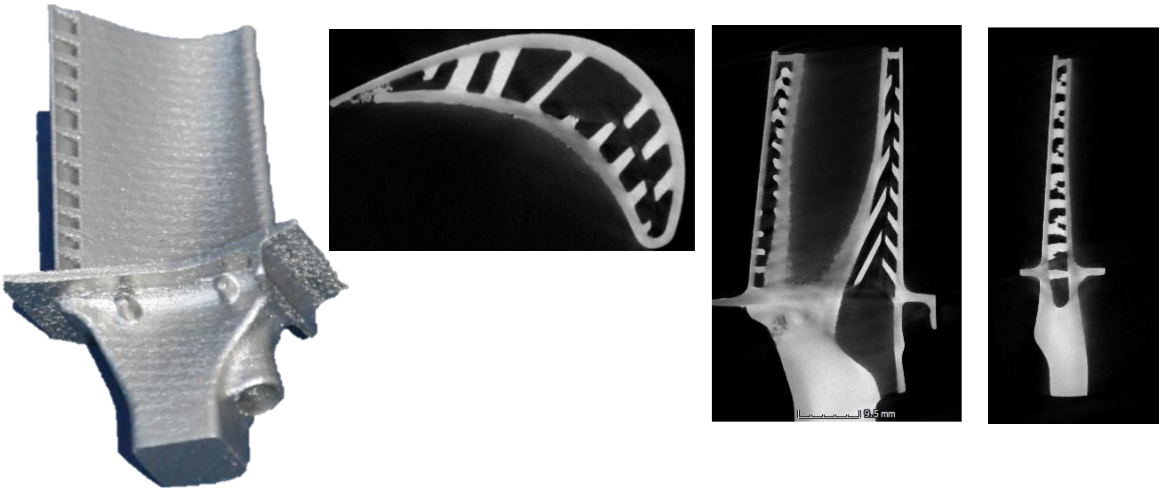
The use of a shell mold with a built-in core allows casting with traditional alloys without the manufacture of lost-wax elements.

3.2.4 Manufacturing of a cooled blade by fused deposition modelling

The process of making a blade can be further shortened by directly printing it from a metal powder alloy using the fused deposition modeling method.

For this purpose, finely dispersed powder materials with a grain size of 6 to 50 μm based on nickel have been developed. Alloys In718 and In625 are intended for use in parts exposed to temperatures up to 850°C. For operation at higher temperatures, heat-resistant nickel alloy powders (ZhS6K, MarM247, etc.) and intermetallic compositions based on CoCrMo and nickel intermetallic compounds such as NiAl and Ni3Al are used [16, 17]. Titan Aluminides can be used for low-pressure turbine blades [18].

The ProX 300 machine, which has a high accuracy (compatible with the EN ISO 2768 standard), was used to manufacture the blades. Test printing was carried out using nickel In718 (10–25 μm) alloy to make it possible to manufacture a thin-walled structure with complex geometric dimensions (Fig. 9a). Tomographic inspection of the printed blades (9b), carried out using a CAT XT H 450 3D/4D computed tomography system (XT H 320), showed good agreement with the blade models.



a) photograph of the printed blade b) tomographic images of the cross-sections of the blade

Figure 9 - Printed nickel alloy blades.

However, the properties of powder metallic materials differ from those of cast materials. Therefore, it is necessary to conduct comprehensive studies of the mechanical and strength characteristics of powder materials to apply this method of manufacturing blades. The parameters of the technical process of growing should be set in such a way that the strength characteristics of the obtained samples meet the requirements for the design and are not less than the characteristics of cast samples.

Thus, the use of AT at one stage or another in the production of blades leads to a significant reduction in time and cost**.**

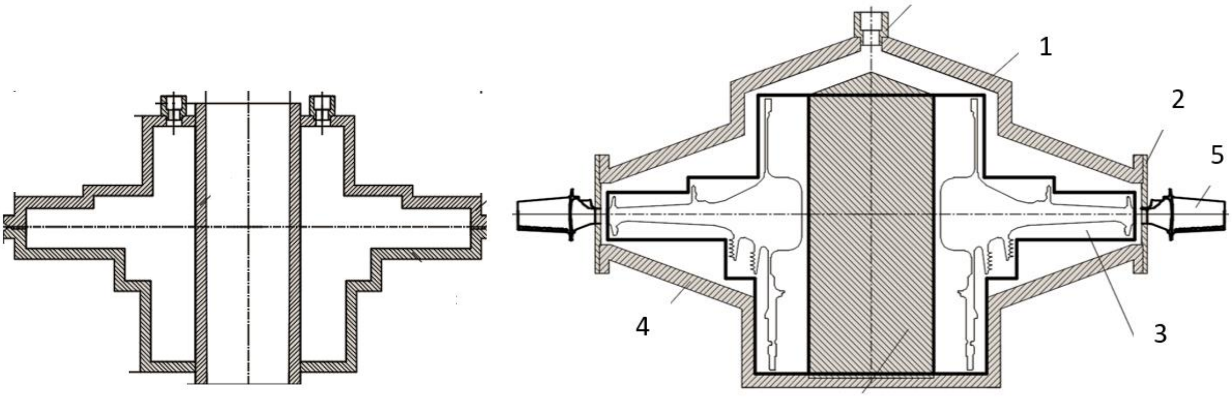
3.3 Blisk making process

Turbine disks are usually made of chromium-nickel alloys with a high nickel content (62–73%). The traditional methods for producing disks are hot deformation (stamping) of blanks with subsequent heat and mechanical treatment [19] and granular metallurgy methods. HIP is a complex of technological processes based on the consolidation of powders of high-alloy alloys, which consists of high-temperature compaction of porous workpieces or powders by high external pressure. Parts such as impellers, diffusers, turbine wheels, and casings are made by HIP.

The advantage of HIP is the ability to obtain products of complex shapes accessible only by casting from hard-to-machine alloys with the strength properties of deformed materials. The production of the part by the HIP method is carried out in a special capsule. The design of the capsule is a deformable tool that determines the initial shape of the workpiece, serves to transmit pressure, and has a decisive influence on its final shape [20]. The complexity of the process, which takes place in a wide range of pressures and temperatures and in the absence of a rigid shaping tool, requires two problems to be solved. The first is predicting the final shape of the workpiece after HIP. The second is creating a capsule design that ensures the manufacture of a product of the required shape and size in the design of the technical process. One important task is the choice of the technology to connect the blades to the disk. Various technologies are being developed for this purpose [3]. To produce disks by HIP methods, heat-resistant nickel alloys with spherical granule sizes of 60–100 μm are used. Solid-phase, defect-free connection of powder particles with each other and with the surface of monolithic materials, realized in the HIP process, opens up the possibility of joining dissimilar materials and designing parts with specified gradient properties and variable chemical composition [6, 7].

Based on this, the following technological chain was proposed for the design developed for the blisk impeller.

- The central part of the blisk disk (Fig. 2) should be manufactured separately to minimize shrinkage during the final molding of the unicycle. The EP741NP granulated nickel alloy is used as a material for the disk. Steel 20 mild steel is used for the manufacture of the capsule. When designing the capsules, the shrinkage of the powder disk material during compaction must be considered. Fig. 10a shows a diagram of a capsule for making a blank disk. The individual elements of the capsule are welded using argon arc welding. When welding the elements of the capsule, all welds must be vacuum-tight, so that the capsule does not depressurize during the compaction process, which would lead to the rejection of the workpiece. A special branch pipe is used to fill the granules into the capsule. After HIP fabrication, the disk is removed from the capsule.



a) for disk blank b) for monowheel

Figure 10 - A diagram of a capsule for making a bimetallic blisk

- Blades are manufactured separately using any of the above methods. The blades are installed in the technological ring, which is an element of the second capsule for manufacturing the blisk structure, and are fixed in it.
- The disk is connected to the blades in the second capsule (Fig. 10b). The capsule consists of shells (1, 4), a technological ring (2) with blades (5), and a disk blank (3). Disk alloy powder is poured into the capsule. The blades are connected to the disk because of the diffusion of a layer of powder located in the gap between them in the process of compaction and deformation of the capsule.

Regarding the design developed for the capsule equipment, was chosen for the initial gap between the central element and the annular assembly of blades and embedded elements. This clearance is necessary for a reliable filling of the powder material and a stable compaction of the powder. The initial density of the powder in the annular gap is selected is ensured by the parameters of the vibration compaction of the granules in the capsule. Analysis of the calculation results showed that the shrinkage is stable and concentrated mainly in the radial direction. Bimetallic blisks for high-pressure GTE turbines have been manufactured with the help of this powder technology (Fig. 1d, 1e) [12].

4. Summery

The possibilities of modern powder technologies to produce structures for GTEs are considered.

Constructive and technological solutions to manufacture turbine impellers using granular metallurgy methods and AT have been developed.

In the example of the design developed for a bimetallic blisk of a high-pressure turbine with cooled blades, the possibilities of using additive and powder technologies to replace various stages of the traditional method of manufacturing blades were considered.

Numerous studies have shown that the absence of lock joints leads to an increase in static strength and cyclic durability. In this case, the mass of the wheel in the form of a bimetallic blisk can be significantly reduced in comparison with the lock structure.

However, since the disks and blisks of turbines are the main parts, the destruction of which can lead to catastrophic consequences, the application of new technologies should be carefully studied by calculation and experimental methods.

References

[1] Inozemtsev A, Anoshkin N, Bashkatov I, Garibov G and Koryakovtsev A. Application of disks from granules of heat-resistant nickel alloys in serial gas turbine engines of aviation and ground equipment. *Advanced technologies of light and special alloys*. Moscow. FIZMATLIT, pp. 371–376, 2006.

[2] Magerramova L, Zaharova T and Kratt E. Design of Hyped compounds of dissimilar heat-resistant alloys for bimetallic blisks of high-temperature gas turbines. *J. Light Alloy Technology,* Vol 3, pp.83-89, 2013.

[3] Strangman T. Integral turbine composed of a cast single crystal blade ring diffusion bonded to a high strength disk. *European Patent Application* EP1728971, 2006.

[4] Lemsky J. Assessment of NASA Dual Microstructure Heat Treatment Method Utilizing Ladish Super-CoolerTM Cooling Technology. *NASA,* Report No. NASA/CR-2005-213574, 2005.

[5] Yegorov D, Garibov G, Grits N, Kazberovich A and Ryzhova N. Investigation of as-HIP PM Ni-Base Superalloy Dual Microstructure Disk Material. *J. Technology of light alloys*. Vol. 3, pp 67-77, 2014.

[6] Garibov G, Grits N, Fedorenko E, Yegorov D, Volkov E and Chudinov A. Investigation of the possibility of manufacturing Dual Structure disks of gas turbine engines with functional gradient properties using powders of various fractions. *J. Technology of light alloys*. Vol. 4, pp. 41-49, 2011.

[7] Kazberovich A, Garibov G, Grits N, Yegorov D and Ryzhova N. P/M VVP-Class Nibase Superalloy Disks with a Dual Structure and Functionally Gradient Properties Manufactured by Direct HIP*. Proc 11th International Conference on Hot Isostatic Pressing*, Sweden: Stockholm, pp. 573-585, 9 - 13 June 2014.

[8] Magerramova L, Noznitsky Yu, Kinzburskiy V and Vasiliev B. The use of additive technologies for the manufacture of parts of advanced gas turbine engines. *J. Light Alloy Technology*, Vol 4, No 4, pp. 7-13 2015.

[9] Navrotsky V. Industrial introduction of additive technologies for the production of gas turbine parts and current operational experience. *J. Gas turbine technologies*, No. 5, pp. 2-10, 2018.

[10]GE9X EBM TiAl Blade industrialization – Avio Aero, novara Cameri, 2019.

[11]Magerramova L, Nigmatullin R, Vasilyev B and Kinzburskiy V. Design of a bimetallic blisk turbine for a gas turbine engine and its production using powder metallurgy methods. *Proc. Turbomachinery Technical Conference & Exposition,* Charlotte, NC, USA, June 27-29, 2017, GT2017-63560.

[12]Magerramova L. The project development of HIPed Bimetallic Blisk with Uncooled and Cooled Blades for Engine Gas Turbine of Difference Using. *Proc. International Conference Hot Isostatic Pressing.* Sweden, No 308, pp 1-8, 2014 id: 140605-1035.

[13]Ospennikova O, Lukin V, Afanasev-Khodykin A, Galushka I. The manufacture of the «blisk» rotor design made from bimetallic combination of materials (review). J. Works of VIAM, No 10(70), pp. 10-16, 2018.

[14]Magerramova L, Kratt E and Yasinsky V. Method of manufacturing integral blisk with cooled blades, integral blisk and cooled blade for gas turbine engine. *Patent RU* 2478796, published 10.04.2013. – bul. No 10, 2013.

[15]Krymov V, Eliseev Yu and Zudin K. *Production of gas turbine engine blades.* Publisher Moscow. Mashinostroenie - Polet. 376 p., 2002.

[16]Kaplanskii Yu, Levashov E, Korotitskiy A, Loginov P, Sentyurina Zh and Mazalov A. Influence of aging and HIP treatment on the structure and properties of NiAl-based turbine blades manufactured by laser powder bed fusion. *Journal Additive Manufacturing*, Vol. 31, 100999, 2020.

[17]Sentyurina Zh. Production of spherical powders from alloys based on nickel aluminide NiAl for additive technologies. *Dissertation, Moscow, National University of Scince and Technology MISIS*, 168 p., 2016.

[18]Bartolotta P. Titanium Aluminide Application in the High Speed Civil Transport. *International Symposium on Gamma Titanium Aluminides.* San Diego, California, Ftbruare 28-March 4, 1999, NASA/TM-1999-209071.

[19]Demin F, Pronichev N, Shitarev I. *Manufacturing technology of the main parts of gas turbine engines.* 2st edition, Publisher SGAU, Samara, 324 p., 2012.

[20]Gang W, Li-Hui L, Xi-Na H and Jia-Jie L. The shielding effect of capsule in the process of Hot Isostatic Pressing. *Proc.13th International Bhurban Conference on Applied Sciences and Technology (IBCAST)* Islamabad, Pakistan 2016.

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